



Research article

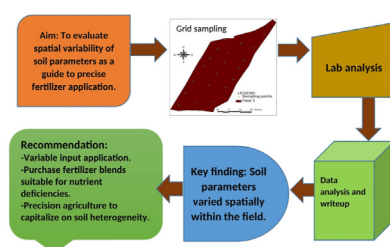
Assessing spatial variability of selected soil properties in Upper Kabete Campus coffee farm, University of Nairobi, Kenya

Samuel M. Mwendwa^{*}, Joseph P. Mbuvi, Geoffrey Kironchi, Charles K.K. Gachene*Department of Land Resource Management and Agricultural Technology, College of Agriculture and Veterinary Sciences, University of Nairobi, P.O. Box 29053-00625, Kangemi, Nairobi, Kenya*

HIGHLIGHTS

- There is need for variable agricultural input application in farms.
- Field spatial variability is a panacea to economically sound soil management.
- Precision agriculture is recommended for profits and environmental protection.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:

Spatial variability
Smart agricultural technology
Variable input application
Precision agriculture
Soil heterogeneity

ABSTRACT

This study aimed to evaluate spatial variability of selected soil parameters as a smart agricultural technology guide to precise fertilizer application. A farm designated as Field 3 which is under Arabica coffee within a bigger Soil Mapping Unit (SMU) was selected for a more detailed soil observation at a scale of 1:5000. Soil samples were taken at depths of 0–15 and 15–30 cm across 20 sample locations in grids and selected properties analysed in the laboratory. Kriging interpolation method was used to estimate the accuracy of interpolation through cross-validation of the top soil parameters. In 0 to 15 and 15–30 cm depth, soil reaction, percentage organic carbon and percent nitrogen showed low variability of 5.1% and 5.8%, 10.4% and 12.7%, 14.5% and 17.6% respectively. Phosphorus was deficient in both depths and showed moderate variability of 36.2% and 42.3% in 0–15 and 15–30 cm respectively. Calcium and Magnesium ranged from sufficient to rich and showed moderate and low variability in top and bottom depths, respectively. All micronutrients were sufficient in the soil. The soils were classified as Mollic Nitisols. Results showed that soil parameters varied spatially within the field therefore, there is need for variable input application depending on the levels of these elements and purchasing of fertilizer blends that are suitable for nutrient deficiencies. Precision agriculture is highly recommended in the field to capitalize on soil heterogeneity.

1. Introduction

Agriculture is the most important economic activity in Kenya (Bauer, 2014) and also specifically in the study area but low soil

fertility, lack of detailed soil information, taxation on agricultural inputs, deleterious impacts of climate change and pests pose a challenge to our agriculture. Land degradation can greatly undermine agricultural production if there is no proper input management (Mugendi

^{*} Corresponding author.

E-mail address: samuelmwendwa2@gmail.com (S.M. Mwendwa).

et al., 2007). Sustainable Development Goals (SDGs) of the United Nation are aimed to combat poverty, reduce desertification, curb climate change and ensure global prosperity which are related to the natural environment and agriculture (World, 2007). The importance of soils in achieving these goals has been highlighted by Keesstra et al. (2016). Soil maps may lead to better understanding of existing nutrient limitations thus allowing easy maintenance of soil fertility through precision agriculture. The major cause of differences in yield or response to inputs is a function of spatial differences within the field. Basso et al. (2011), Muschietti-Piana et al. (2018), Nyéki et al. (2021) and Nyéki et al. (2022) recommended that variable input application in fields has the ability to increase yields and reduce environmental impact.

Spatial variability of soil parameters is paramount in the explanation of the influence of the factors of soil genesis and land use on soils. It permits the use of different tracks of land for different purposes and is the central concept in soil mapping. A study by Franzluebbers and Hons (1996) compared the distribution of available soil nutrients in fields under different farming systems and recommended the importance of having soil information as a guide to soil management. Farming decisions should always be based on soil management zones in support of precision agriculture (Kathumo, 2007; Ali et al., 2022). Management zones delineate farms on basis of soil attributes to guide fertilizer application (Fridgen et al., 2004; Bao-wei et al., 2018; Ali et al., 2019; McEntee et al., 2020; Ali et al., 2022).

Other than the factors of soil genesis, management history is also crucial in determining the productivity of a given soil (McBratney et al., 2003; Pendleton and Jenny, 1945). Soil variability results mainly from complex interactions among topography, geology and climate coupled with land use (Behera et al., 2016; Liu et al., 2015) therefore soils exhibit marked spatial variability at macro and micro-scale (Shukla et al., 2016). Field operations including fertilization, tillage and manure application are also sources of variability at various scales of distance and time (Kathumo, 2007) therefore awareness of this heterogeneity for sustainable agricultural production and increasing profitability is paramount.

Spatial variability is the combined effect of chemical, physical and biological processes occurring at different spatiotemporal scales coupled with anthropogenic activities (Goovaerts, 1998). It can help to correct nutrient deficiencies (Brevik and Miller, 2015) and to determine production constraints related to soil fertility. Spatial variability of soils can also act as a guide in suggesting variable remedial measures for optimum production and appropriate land use practises sustainable in the long run (Hålbac-Cotoară-Zamfir, 2019; Panday et al., 2018). Spatial variability of soil properties is assessed effectively by geostatistical techniques (Emadi et al., 2016; Liu et al., 2014; Moosavi and Sepaskhah, 2012; Moradi et al., 2016; Shahabi et al., 2016) which can explain the extent of soil variability. Soil heterogeneity has been studied under different management systems (Behera and Shukla, 2015). Spatio-statistical tools predict the values for unsampled locations by factoring in the geographical association between sampled and projected points and reducing variance of assessment error and costs (Behera and Shukla, 2015).

Developments in computing techniques and remote sensing technology provide opportunities for more data-driven applications in farm management. This approach is referred to as smart farming (Wofert et al., 2017) or precision agriculture. Remote sensing and GIS helps to manage in-field variability, a technology known as precision agriculture (Robertson et al., 2012) that uses information tools including the Global Positioning System; GPS (Aubert et al., 2012; Llewellyn and Ouzman, 2014). This technology requires an enabling institutional, technical and social environment, high skill, competent interpretation and judgement therefore posing a challenging adoption scenario.

Precision Agriculture (PA) technology has undisputable benefits in agriculture as it can improve the efficiency of farm operations by

applying exactly what the crops require and saving on the excess (Eastwood et al., 2017; Smith et al., 2013). It can improve water quality and conserve the environment (Lundström and Lindblom, 2016). Recognition of field variation enables the application of variable rate treatments with fine degrees of precision than it would be without point based soil information (Lindblom et al., 2017), therefore representing a paradigm shift in farm practises. PA technology considers a field as a heterogeneous entity eligible for selective treatment (Aubert et al., 2012). Spatial variability for PA studies have been done in many parts of the world using different approaches (Castaldi et al., 2017; Kandagor, 2015; Morari et al., 2018).

Increasing population has been shown to decline agricultural productivity (Muyanga and Jayne, 2014) therefore there is need to utilize the remaining land appropriately for maximum agricultural production. Blanket application of agricultural inputs is a common practise in the study area. There is no consideration of soil heterogeneity as a guide to variable fertilizer application. This practice presents a major agricultural challenge and therefore a research gap. Despite the area having favourable climate for production of coffee and other crops, coupled with favourable soil conditions for agriculture, harvests are usually subpar. This is due to inappropriate management of the farms, more specifically the failure to understand the nexus between crop nutrient requirements and soil properties. The key objective of this study was to evaluate the spatial variability of selected soil parameters in the study area so as to guide decisions on input application. This was driven by the existence of within-field variability in nearby fields (Kandagor, 2015) and also in other parts of the world. It was also motivated by the potential for better crop productivity with knowledge on point-based soil information.

Coffee production in Kenya in smallholder and also in plantations has declined in the last 30 years both in terms of quality and quantity. This could be due to minimal or lack of proper soil management as reflected in Upper Kabete Campus coffee farms. Assessing the spatial variation of selected soil properties will determine the soil management practices to be undertaken. This study will help to improve the floral integrity of the coffee, thereby improving on production.

2. Materials and methods

2.1. Description of the study site

This study was done in a selected farm (Figure 1; 5.87 ha) in upper Kabete campus field, University of Nairobi. The farm (Field 3) lies between 248599 longitude, latitude 9861349 latitude and 1842 altitude (Universal Transverse Mercator; UTM) according to Mwendwa et al. (2019) and Mwendwa et al. (2020). It is part of the Loresho Ridge which is an upland characterized by slopes ranging from 0 to 32% (Mwendwa et al., 2020) and categorized under Agro-Climatic Zone III. The rainfall is bimodal in distribution and the climate is typically sub-humid (Jatzold and Kutsch, 1982). The geology comprises the Kabete grey-green porphyritic trachyte of middle division of tertiary age (Mathu and Mwea, 2014; Onyancha et al., 2011) overlying the Nairobi trachyte and Kirichwa valley tuffs. These rocks are overlain elsewhere by the Limuru-Karura trachytes and are equivalent in age to the Ruiru dam trachyte. The farm is under arabica coffee therefore most of the discussions were based on coffee crop management. It was selected as an ideal site for soil characterization at a detailed level and because various seasonal crops are usually planted at different sections of the coffee field, a practise hypothesized to induce soil heterogeneity.

2.2. Soil sampling

The key goal of soil sampling was to accurately characterize the nutrient status of the soil. Sample locations in Field 3 were geo-referenced using a GPS to allow correlation of soil test results with spatial

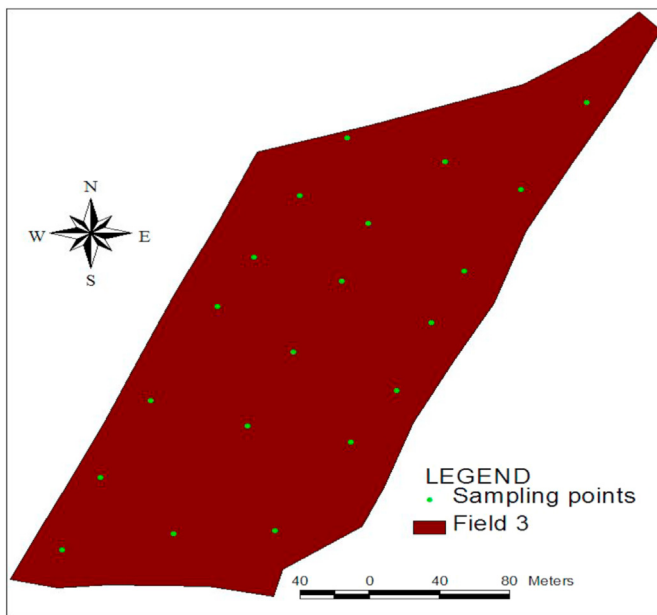


Figure 1. Study area (Field 3) showing sampling points.

details of the soil sample (Figure 1). Samples were collected at 0 to 15 and 15–30 cm depths in twenty (20) sampling points across the farm at a distance of approximately 50 m from one observation to the other in grids. This constituted 20 samples per depth, totalling to 40 samples for chemical analysis. A soil auger was used to scoop soil samples from both depths and there were two buckets for the two depths. Non-typical sections of the farm were not sampled including near the edges. A composite soil sample was collected whereby at every sampling point, five samples were taken from each depth within a radius of three metres, thoroughly mixed and only half of a kilogram sample was taken from the mixture. The sample was well labelled and taken to the laboratory for preparation which included air drying and sieving.

2.3. Soil analysis

Sample preparations were done at the departmental laboratory before analysis. Soil reaction was measured with a glass electrode pH meter (Baillie et al., 1990). Total organic carbon (C), available phosphorus (P) and total nitrogen (N) were determined using the Walkley-Black method as lucidly exposed by Nelson and Sommers (1996), Molybdenum Blue technique (Baillie et al., 1990) and Kjeldahl steam distillation (Baillie et al., 1990; Black et al., 1965) respectively. Exchangeable potassium (K) and exchangeable sodium (Na) were measured using a flame photometer; exchangeable calcium (Ca) and exchangeable magnesium (Mg) were analysed using the Atomic Absorption Spectrophotometer (AAS) at element specific spectral signatures. Manganese (Mn), zinc (Zn), copper (Cu) and iron (Fe) were analysed in the Atomic Absorption Spectrophotometer (AAS) equipment from the available P extract after the P aliquot had been taken. These methods are in Baillie et al. (1990).

Determination of soil reaction involved weighing and shaking of the samples in solution at the ratio of 1:2.5 (soil:distilled water), calibration of the pH meter and reading of the samples. Analysis of carbon involved digesting the samples with potassium dichromate ($K_2Cr_2O_7$) in the presence of concentrated H_2SO_4 and titration using 0.5N of $FeSO_4$. Molybdenum blue technique is part of the Mehlich 1 protocol which involves extracting the phosphorus from the soil using double acid ($HCl + H_2SO_4$) through shaking, development of colour and quantification of the absorbance using UV. Kjeldahl method involves digesting the sample using concentrated H_2SO_4 in the presence of mixed catalyst, steam

distillation to obtain the ammonia in 2% boric acid and titration using 0.01N H_2SO_4 . Exchangeable K and Na are measured in flame photometer after activating the element. The Atomic Absorption Spectrophotometer (AAS) measures absorbance of Ca, Mg and the selected microelements at element-specific wavelengths.

2.4. Generation of spatial variability maps

Kriging procedure was used to generate soil variability maps to guide input management. The software operation procedure for generation of the maps was according to that in Mwendwa et al. (2020). Maps for micronutrients were not presented in this study because there were no management zones required as the elements are sufficiently supplied in the soil and also because this study was approached from a management point of view. Maps showing a single zone were also not presented.

2.5. Cross-validation of the kriging procedure

A semivariogram was not fitted because Kriging requires at least 30 data points to generate the nugget, sill and range. The root mean square error (RMSE) was calculated to evaluate the accuracy of the interpolation method. The following formula (Eq. 1) was used to calculate the RMSE of the model.

$$RMSE = \frac{\sqrt{\sum_{i=1}^N (O_i - S_i)^2}}{N} \quad (1)$$

Where, O_i is the observed value, S_i is the predicted value and N is the number of samples.

2.6. Soil classification

The larger area within which this study was done involved digging of soil profiles, horizon description, soil sampling and analysis and a detailed characterization of the soils, with Soil Mapping Units (SMUs) based on slope categories. The IUSS Working Group WRB, 2014 (Schad, 2017) was used in soil classification as the larger area within which this study was done involved detailed soil survey and classification.

2.7. Statistical analysis

Descriptive statistics was done using SPSS to obtain the coefficient of variation (%cv). Guidelines used to classify the coefficient of variation (% cv) were: $cv < 25\%$ = low, $cv = 25\text{--}50\%$ = moderate, $cv > 50\%$ = high variation. Other parameters including the mean, median, standard error, standard deviation, sample variance, kurtosis, skewness, range, minimum and maximum were also generated.

3. Results and discussion

3.1. Diagnostic horizons and properties

A nitic B horizon and a mollic A horizon were identified through observation and laboratory analysis. In the study area, only Nitisols were identified as influenced by climate and geology of the study site. Nitisols had a nitic horizon with less than 20 percent relative change in clay content over 15 cm to layers immediately above and below; 30 percent or more clay; a silt to clay ratio less than 0.4; moderate to strong, subangular blocky structure breaking to flat-edged or nut shaped elements with shiny ped faces attributed to clay illuviation, a thickness of 30 cm or more and gradual, smooth boundary between A and B horizons. Only Mollic Nitisols were found because of the occurrence of a mollic A horizon; Very fine, mixed, isothermic Oxic Humiustalf: Soil Taxonomy (Mwendwa et al., 2020).

3.2. Cross-validation

Kriging method was cross-validated at each sampling location by comparing approximated values with actual values (Table 1). The RMSE was small (<0.5) for pH, organic carbon, nitrogen, potassium and sodium indicating that the interpolation model was an adequate representation of the spatial properties of the soil. It demonstrated a lack of logical bias for forecast spatial distribution therefore the projected maps of the soil properties and the results were consistent. Values for phosphorus, magnesium, calcium and micronutrients indicate a moderate prediction quality of the interpolation method.

3.3. Descriptive statistics

The coefficient of variation (cv%) was used to express the extend of spatial variability of the soil properties. The number of samples in question was 20 (n = 20). Soil reaction showed the lowest variability (5.1% and 5.8%) in 0–15 and 15–30 cm respectively. This indicates that the soil reaction is similar over a large area and therefore a wide sampling range would be appropriate for soil pH studies in the area. The values of skewness and kurtosis were near zero indicating that the data distribution did not deviate largely from the normal distribution. The standard deviation was used to indicate the shape of distribution in relation to the mean. Most of the values in this study are near zero indicating that the data values are concentrated around the mean. The standard error was used to indicate the reliability of the mean whereby a small SE was interpreted as a more accurate reflection of the actual population mean. Most of the values in this study are near zero indicating an accurate representation of the actual population mean. The maximum and minimum values indicate no evidence of outliers, deviating by slight margins from the mean. Summary statistics for both depths are presented in Table 2 and Table 3.

3.4. Spatial variability of selected soil properties

There was evidence of spatial variability in the selected farm. The tested parameters were presented alongside their degree of variability within the farm. Similar spatial variability of soil properties has been identified by previous studies including: Scudiero et al. (2018), Nyéki et al. (2021) and Nyéki et al. (2022).

3.4.1. Soil reaction (pH H₂O)

It determines nutrient availability and the rate of microbial reactions (Yan et al., 2019). The pH varied from strongly acid to medium acid (5.1–6.0) with a mean of 5.6 in 0–15 cm and strongly acid to slightly acid (5.1–6.3) with a mean of 5.8 in 15–30 cm (Figure 2 and Figure 3). It shows low variability of 5.1 and 5.8% in top and subsoil, respectively. In the 0–15cm depth, strongly acid covers an area of 2.03 ha while medium

acid covers an area of 3.84 ha while in 15–30 cm depth, slightly acid covers 0.60 ha, medium acid 4.58 ha and strongly acid 0.69 ha. The acidic pH of the soil can be attributed to leaching of basic cations under the humid conditions which is demonstrated by higher pH values in 15–30 cm depth. In a similar study in Nepal, Panday et al. (2018) attributed moderately acidic soil reaction to leaching of major cations. Predominantly acidic pH can also be attributed to incessant uptake of cations by coffee feeder roots in the upper depth and this observation is consistent with findings of Khadka et al. (2017) who found variable pH in a single farm in Dhanusha, Nepal. The pH range is favourable for the growth of Arabica coffee as it is known to grow in soil conditions ranging from acidic to neutral (pH 4 to 7). This is in accordance with Veedhi (2008) and Nzeyimana et al. (2020) who documented acidic soil reaction as appropriate for optimal coffee production.

3.4.2. Organic carbon (%OC)

It is the precursor to organic matter and plays a crucial role in maintaining the soil structure and binding nitrogen thus improving infiltration and plant uptake, respectively. The correlation coefficient (r) for carbon and nitrogen is 0.2 and 0.3 in 0–15 and 15–30 cm, respectively. This observation is consistent with findings of Cheng et al. (2016) and Lelago and Buraka (2019) who found that organic carbon is essential for nitrogen availability. It is also consistent with the findings of Ye et al. (2021) who observed a positive correlation between soil nitrogen and soil carbon. Organic carbon ranges from 2.12 to 3.18% with a mean of 2.75% in 0–15 cm, showing adequate status. It ranges from 1.82 to 3.07% with a mean of 2.40% in 15–30 cm, showing moderate to adequate status (Figure 4). Both top and bottom depths show low variability (10.4 and 12.7%), respectively. In 15–30 cm depth, organic carbon was moderate in 0.15 ha and adequate in 5.72 ha. Higher organic matter content in top horizon can be attributed to more litter on the surface, an observation consistent with findings of Browaldh (1995) who attributed higher organic matter in top horizons to more litter. Higher soil carbon in the top soil horizon has also been identified in a previous study by Madigan et al. (2022), who attributed the phenomenon to increased decomposition as a result of increased faunal activity compared to bottom horizons. In terms of coffee production, these values are rated as low (Table 4) therefore 3–5 tonnes/ha of well-decomposed animal manure should be added per year to improve nutrient supply. Variability in soil carbon can be attributed to differences in farm management and fertilization strategies as different parts of the coffee farm are intercropped with seasonal crops during rainy seasons. This observation agrees with the findings of Zhao et al. (2021), Li et al. (2021) Jaksiet al. (2021) and Wu et al. (2022), who identified heterogeneity of soil carbon in studied fields.

3.4.3. Total nitrogen (%N)

It is vital for crop nutrition (Farzadfar et al., 2021) and for vegetative development and is most frequently deficient in soils across the world (Ullah et al., 2010). In 0–15 cm, it ranges from 0.23 to 0.38% with a mean of 0.32%. In 15–30 cm, percent nitrogen ranges from 0.21 to 0.35% with a mean of 0.29%. All samples are in medium category. Both top and bottom depths show low variability (14.5% and 17.6%), respectively. These values are relatively lower than the critical levels (0.3–0.6%) for optimal coffee production as recommended by The Coffee Research Foundation (CRF). The decline in percent nitrogen levels can be attributed to continuous cultivation without nutrient replenishment especially manure. This is consistent to findings of Willy et al. (2019), who attributed declining soil nitrogen to continuous cultivation. Application of NPK fertilizer at the rate of 250 g per coffee tree biannually is recommended.

3.4.4. Available phosphorus (P)

It is important in metabolism and transformation of energy in plants (Rai et al., 2011; Ducouso-Détrez et al., 2022) and plays a vital role in coffee in developing the bearing branches. Phosphorus is deficient in the studied farm, having a mean of 10.65 and 10.31 ppm and showing

Table 1. Cross-validation results for 0–15 cm depth as a test for the accuracy of the interpolation model.

Soil Property	RMSE
Soil pH	0.260
Organic Carbon (%)	0.319
Nitrogen (%)	0.058
Phosphorous (ppm)	4.485
Potassium (cmol (+)/kg)	0.485
Sodium (cmol (+)/kg)	0.086
Magnesium (cmol (+)/kg)	0.561
Calcium (cmol (+)/kg)	2.664
Iron (ppm)	13.824
Copper (ppm)	2.731
Manganese (ppm)	23.391
Zinc (ppm)	7.795

Table 2. Summary statistics for 0–15 cm depth in Upper Kabete Campus coffee farm (Field 3).

Soil property	Mean	SE	Median	SD	SV	Kurtosis	Skewness	Range	Min	Max
pH (H ₂ O)	5.59	0.064	5.6	0.285	0.081	-1.090	-0.223	0.9	5.1	6
%OC	2.749	0.063	2.85	0.283	0.080	-0.283	-0.606	1.06	2.12	3.18
%N	0.32	0.01	0.34	0.04	0.001	0.211	-0.788	0.15	0.23	0.38
P (ppm)	10.65	0.741	10	3.313	10.976	-0.342	0.641	12	6	18
K (cmol (+)/kg)	2.185	0.099	2.25	0.444	0.197	-0.862	-0.238	1.5	1.5	3
Na (cmol (+)/kg)	0.165	0.011	0.2	0.049	0.002	-1.719	-0.681	0.1	0.1	0.2
Mg (cmol (+)/kg)	2.9205	0.144	3.04	0.646	0.417	0.611	-0.540	2.71	1.5	4.21
Ca (cmol (+)/kg)	9.81	0.577	9.55	2.580	6.658	-0.548	-0.121	10	4.5	14.5
Fe (ppm)	44.25	3.238	44.5	14.480	209.671	-1.063	-0.159	49	19	68
Cu (ppm)	18.8	0.541	19	2.419	5.853	0.624	-0.285	10	13	23
Mn (ppm)	71.45	5.095	80.5	22.784	519.103	2.499	-2.007	69	17	86
Zn (ppm)	30.3	1.786	31	7.987	63.800	-1.062	-0.016	27	17	44

Table 3. Summary statistics for 15–30 cm depth in Upper Kabete Campus coffee farm (Field 3).

Soil property	Mean	SE	Median	SD	SV	Kurtosis	Skewness	Range	Min	Max
pH (H ₂ O)	5.755	0.074	5.75	0.330	0.109	-0.688	-0.221	1.2	5.1	6.3
%OC	2.3975	0.068	2.425	0.304	0.092	0.226	0.166	1.25	1.82	3.07
%N	0.29	0.01	0.305	0.045	0.002	-1.26	-0.39	0.14	0.21	0.35
P (ppm)	10.35	0.979	9.5	4.380	19.187	-0.298	0.268	17	2	19
K (cmol (+)/kg)	1.74	0.113	1.85	0.504	0.254	-0.208	-0.726	1.8	0.6	2.4
Na (cmol (+)/kg)	0.165	0.011	0.2	0.049	0.002	-1.719	-0.681	0.1	0.1	0.2
Mg (cmol (+)/kg)	2.702	0.116	2.88	0.519	0.270	-0.658	-0.757	1.64	1.68	3.32
Ca (cmol (+)/kg)	10.55	0.615	11.25	2.751	7.570	-0.026	-0.640	10.4	3.8	14.2
Fe (ppm)	48.65	3.937	48	17.605	309.924	-0.002	0.777	61	28	89
Cu (ppm)	15.4	0.600	15	2.683	7.200	-0.742	0.395	9	12	21
Mn (ppm)	74.25	1.196	75	5.350	28.618	-0.416	-0.592	19	63	82
Zn (ppm)	23.8	2.051	24.5	9.174	84.168	-0.344	0.065	34	9	43

Legend: SE = Standard Error; SD = Standard Deviation, Min = Minimum; Max = Maximum.

moderate variability (36.2 and 42.3%) in 0–15 and 15–30 cm, respectively. These values were below the critical level (20–100 ppm) for coffee production as per the CRF recommendations. Phosphorus deficiency can be attributed to its attachment to sediments and subsequent transportation through erosion and also the acidic pH of the soils that could have led to P fixation. This observation is consistent with findings of [Bakhshandeh et al. \(2014\)](#) in Lahijan, Iran, who attributed P deficiency to fixation in acidic soil reaction. This finding also agrees with conclusions of [Nadeem et al. \(2022\)](#). The aggravations of phosphorus deficiency in the soil as a result of sediment detachment, transportation and deposition in other areas is consistent with the observations of [Alewell et al. \(2020\)](#) and those of [Ferreira et al. \(2022\)](#), who pointed out that erosion induces phosphorus deficiency in soils. The deficiency could also be due to soil development from a phosphorus-deficient parent material, an observation consistent with findings of [Porder and Ramachandran \(2013\)](#), [Ringeval et al. \(2017\)](#) and [Ducouso-Détrez et al. \(2022\)](#), who found that parent materials had a great influence on the amount of phosphorus in the soil. Phosphorus deficiency in soils is a global issue threatening the accomplishment of United Nations Sustainable Development Goal Number Two, Zero Hunger. This statement has been echoed by previous studies ([Hao et al., 2022](#)). Application of 3–5 tonnes/ha of well-decomposed animal manure is recommended as manure would increase the number of colloids with low phosphate fixation in the like of organic matter.

3.4.5. Exchangeable potassium (K)

Potassium is vital for maintenance of physiological processes, protein synthesis and maintaining plant water balance ([Sumithra et al., 2013](#); [de Bang et al., 2021](#)). In 0–15 cm, K varies from 1.5 to 3.0 cmol

(+)kg⁻¹ with a mean of 2.19 cmol (+)kg⁻¹. It indicates rich supply and shows low variability (21.7%). In 15–30 cm, K ranges from sufficient to rich (0.6–2.4 cmol (+)kg⁻¹) with a mean of 1.74 cmol (+)kg⁻¹ and shows moderate variability of 28.9% ([Figure 5](#)). These observations indicate adequate status of potassium enough for coffee nutrition based on K values between 0.4 to 2.0 cmol (+)kg⁻¹ which are the recommended rates for optimal coffee production. Soils of the study area were derived from volcanic activities hence are rich in K and that could have led to the adequate K in the soils. This finding is consistent with the review of [Swoboda et al. \(2022\)](#) about remineralizing soils, that concluded that parent materials exert great influence on the soil K availability.

3.4.6. Exchangeable calcium (ca)

Calcium regulates how plants respond to endogenous stimuli and signals of stress ([Lecourieux, 2006](#); [Blanco et al., 2020](#)). It ranges from 4.5 to 14.5 cmol (+)kg⁻¹ with a mean of 9.79 cmol (+)kg⁻¹ in 0–15 cm. It ranges from 3.8 to 14.2 cmol (+)kg⁻¹ with a mean of 10.54 cmol (+)kg⁻¹ in 15–30 cm. Both depths indicate sufficient to rich supply ([Figure 6](#) and [Figure 7](#)). It shows moderate variability of 26.3% in both depths too. In 0–15 cm, sufficient covers an area of 3.17 ha while rich covers an area of 2.70 ha whereas in 15–30 cm depth, sufficient covers an area of 0.17 ha while rich covers an area of 5.70 ha. Observed values are sufficient for optimum production of coffee given the critical values (1.6–10 cmol (+)kg⁻¹) as per Coffee Research Foundation. Deficiency of phosphorus could have compromised the uptake of Ca therefore its (phosphorus) remedial fertilization is encouraged to boost Ca uptake. Slightly higher Ca content in the 15–30 cm depth could be a result of leaching in the humid environment, a suggestion consistent with the findings of [Ng et al. \(2022\)](#) that

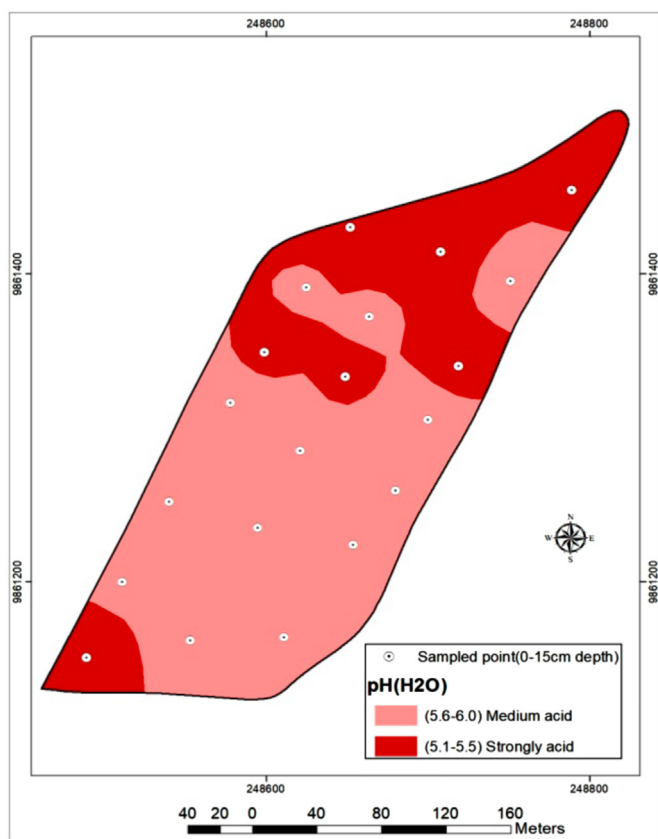


Figure 2. Spatial distribution of pH in the 0–15 cm depth in Upper Kabete Campus coffee farm (Field 3).

noted the leaching of base cations in the soil as the reason for higher base concentrations in bottom soil depths.

3.4.7. Exchangeable magnesium (Mg)

Magnesium plays an array of vital roles in plants including enzyme catalysis, photosynthesis and synthesis of the genetic material (Tanoi and Kobayashi, 2015). In 0–15 cm depth, magnesium varies from 1.50 to 4.21 cmol (+)kg⁻¹ with a mean of 2.92 indicating sufficient status and showing low variability of 22.1% (Figure 8). In 15–30 cm depth, Mg ranges from 1.68 to 3.32 cmol (+)kg⁻¹ with a mean of 2.54 indicating sufficient supply (Figure 9) and showing low variability (19.2%). In 0–15 cm, sufficient covers an area of 2.05 ha while rich covers an area of 3.82 ha. In 15–30 cm depth, sufficient covers an area of 0.11 while rich covers an area of 5.76 ha. These values are within the critical values (0.8–4.0 cmol (+)kg⁻¹) for optimum production of coffee as adopted at CRF. Higher Mg content in the lower depth can be attributed to leaching in the humid environment. Magnesium leaching in the soil was also observed in other studies including Zhang et al. (2021) and Ng et al. (2022).

3.4.8. Exchangeable sodium

It is a monovalent so it can be a substitute for K in plant nutrition but its excess could be detrimental to the soil structure due to sodicity. All samples from both depths have sodium values ranging from 0.1 to 0.2 cmol (+)kg⁻¹ with a mean of 0.2 cmol (+)kg⁻¹ indicating non-sodicity. It shows moderate variability (45.3 and 33.6%) in 0–15 and 15–30 cm depth, respectively. These values are adequate therefore sodium is not a limitation to coffee production.

3.4.9. Available: iron (Fe), zinc (Zn), copper (Cu) and manganese (Mn)

Iron is the most essential micronutrient for its role in chlorophyll synthesis and electron transport. It impacts nitrification, respiration and synthesis of genetic materials (Yadegari, 2014). Iron varies from 19 to 68

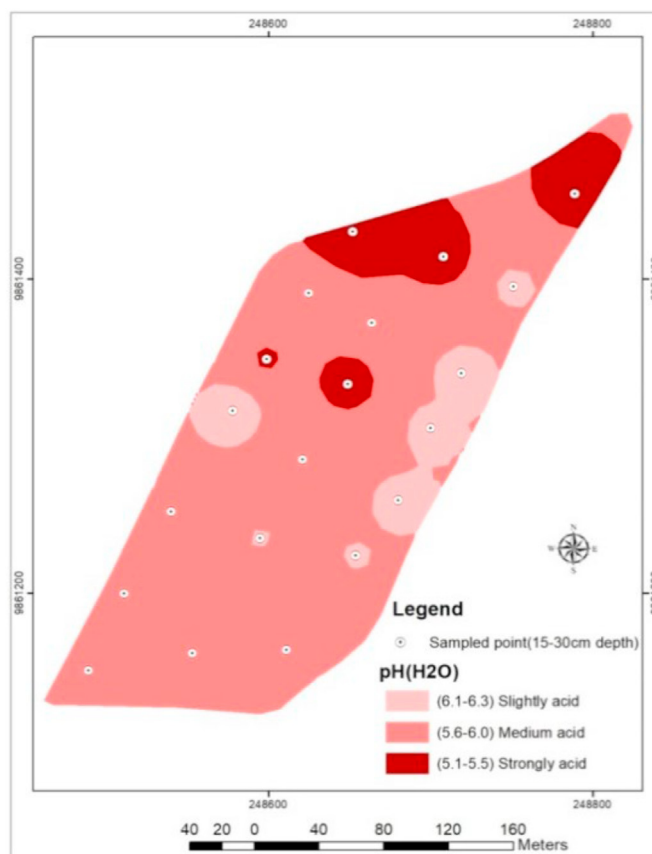


Figure 3. Spatial distribution of pH in 15–30 cm depth in Upper Kabete Campus coffee farm (Field 3).

ppm with a mean of 44.15 ppm in 0–15 cm and 28–82 ppm with a mean of 48.65 ppm in 15–30 cm. It indicates sufficient status and shows moderate variability (32.8 and 36.1%) in top and bottom depths,

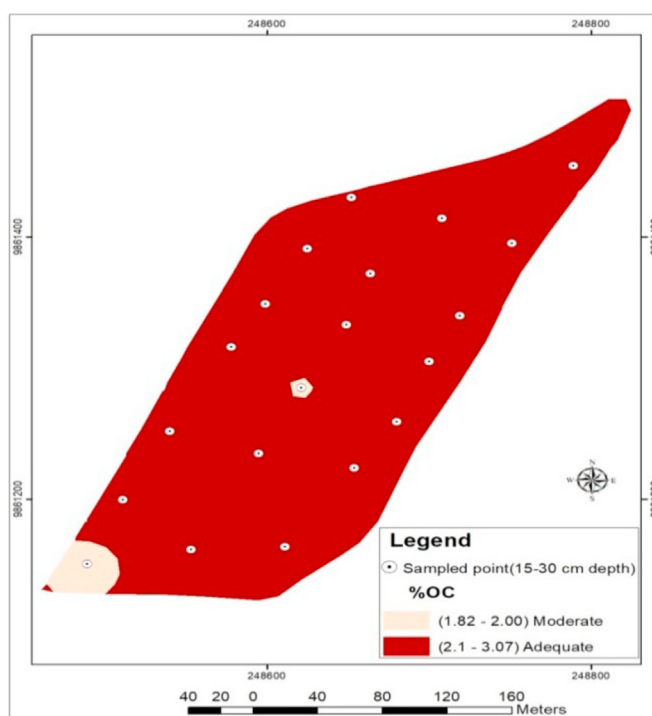


Figure 4. Spatial distribution of %OC in 15–30 cm depth in Upper Kabete Campus coffee farm (Field 3).

Table 4. Soil critical ratings for total carbon and total nitrogen.

Rating	Total Carbon (%)	Total Nitrogen (%)
Very high	>20	>1.0
High	10–20	0.6–1.0
Medium	4–10	0.3–0.6
Low	2–4	0.1–0.3
Very low	<2	<0.1

Source: NARL

respectively. The rich iron status across all samples can be attributed to good drainage and Fe availability in the exchange complex after leaching of bases. It can be concluded that the soils of Kabete are rich in iron but the status is not toxic to coffee production. The rich status of iron suggests high probability of iron-rich minerals including hematite, goethite, olivine, magnetite and siderite being available. It may also be a function of Fe complexes with phosphate substances in the soil, inducing limited chance for leaching losses. Nutrients including P, K, Mn and Zn should be well managed as their availability is inhibited by high iron availability (Fageria et al., 2008).

Zinc plays a key function in gene replication and a vital role in plant metabolism by influencing hydrogenase and carbonic anhydrase activity, cytochrome synthesis and stabilizing ribosomal fractions (Maleki et al., 2014). It ranges from 17 to 44 ppm having a mean of 30.23 ppm in 0–15 cm and 9–43 ppm with a mean of 23.76 ppm in 15–30 cm. Both top and bottom depths are sufficient in Zn and show moderate variability (26.5 and 38.8%), respectively. High zinc status in the soil can be attributed to the igneous parent material of the study area which is usually rich in Zn. In a study in Nepal, Panday et al. (2019) observed low Zinc status across the entire study area and attributed it to the predominantly alkaline soil pH. This is agreeable based on the fact that most micronutrient elements are deficient at high pH.

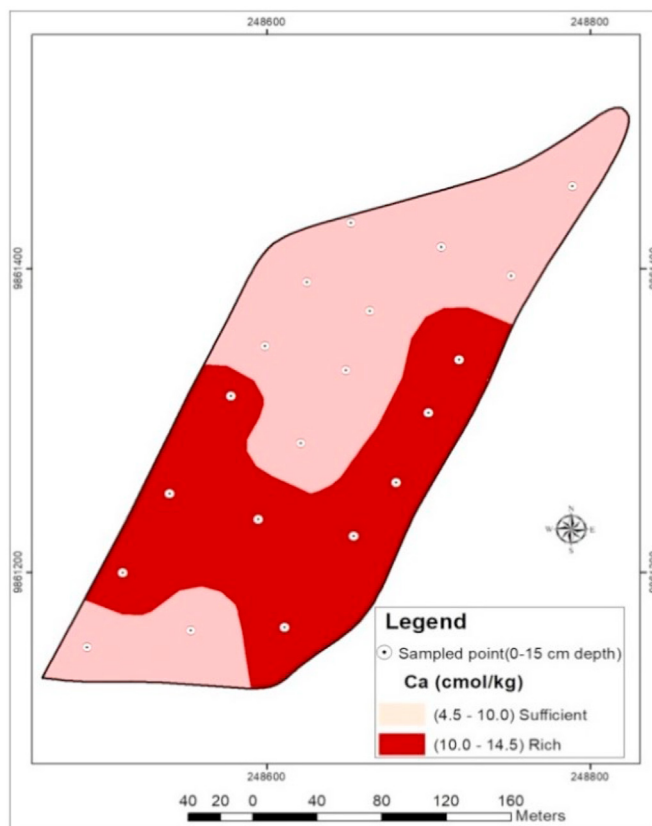


Figure 6. Spatial distribution of Ca in 0–15 cm depth in Upper Kabete Campus coffee farm (Field 3).

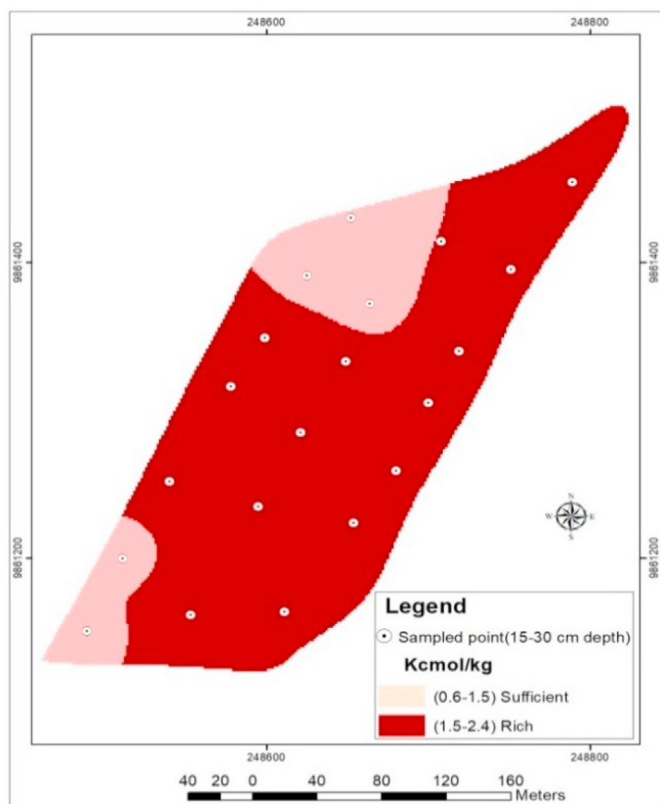


Figure 5. Spatial distribution of K in 15–30 cm depth in Upper Kabete Campus coffee farm (Field 3).

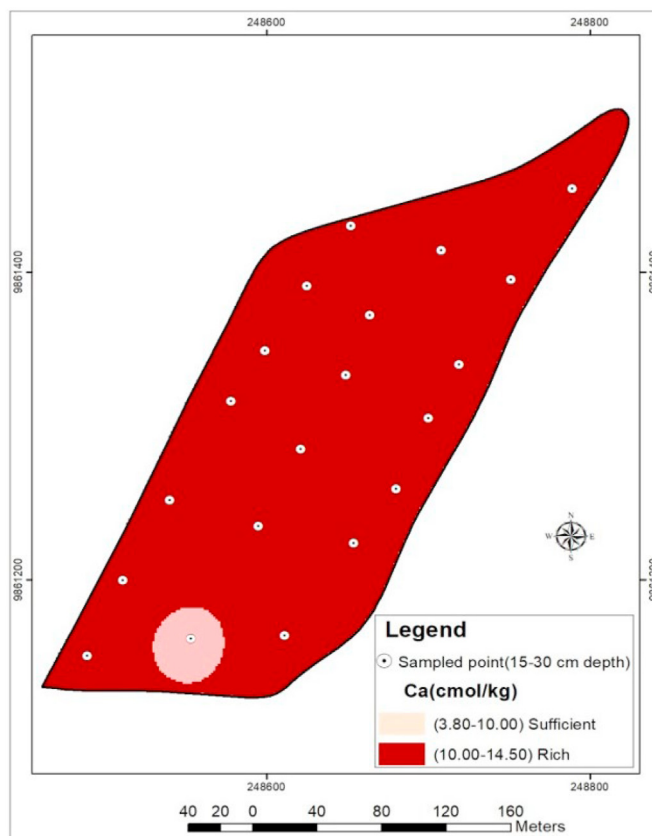


Figure 7. Spatial distribution of Ca in 15–30 cm depth in Upper Kabete Campus coffee farm (Field 3).

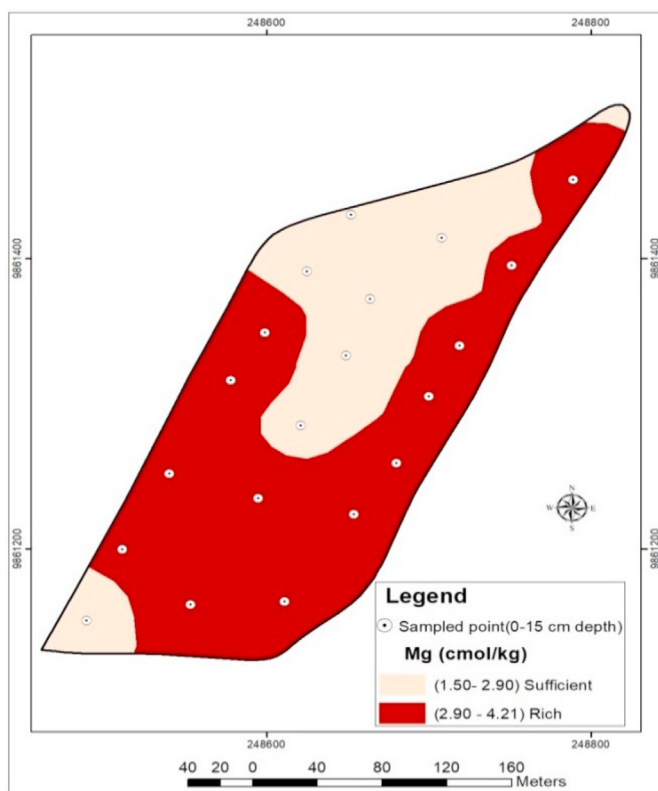


Figure 8. Spatial distribution of Mg in 0–15 cm depth in Upper Kabete Campus coffee farm (Field 3).

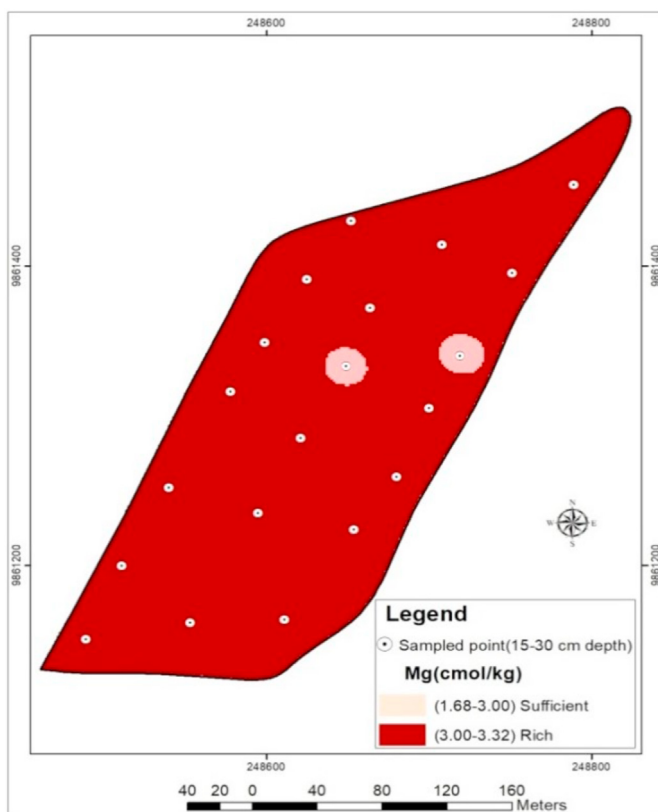


Figure 9. Spatial distribution of Mg in 15–30 cm depth in Upper Kabete Campus coffee farm (Field 3).

Copper facilitates mitochondrial respiration, hormone signalling, photosynthetic electron transport and enzyme activation in plants (Adhikari et al., 2016). It ranges from 13 to 23 ppm with a mean of 18.76 ppm in 0–15 and 12–21 ppm having a mean of 15.41 ppm in 15–30 cm. All samples are sufficient in Cu and show low variability (13.3 and 17.3%) in 0–15 and 15–30 cm depth, respectively. The sufficient status of copper and higher concentration in the top horizon can be attributed to clay mineral and organic matter, respectively. This is because copper exists in soil mainly as a divalent Cu^{2+} ion adsorbed by clay minerals or associated with organic matter. It can also be attributed to low soil Phosphorus which is known to be a contradictory factor to copper availability.

Manganese originates primarily from decomposition of ferromagnesian rocks. It is important in photosynthesis, nitrogen assimilation, root pathogen resistance and enzyme activation (Marschner, 1995; Uthman et al., 2022). In 0–15 cm, it ranges from 17 to 86 ppm with a mean of 71.33 ppm and shows moderate variability (32%). In 15–30 cm, Mn varies from 63 to 82 ppm, having a mean of 74.19 ppm and shows low variability (7.1%). These values indicate sufficient supply of Mn in the soil and is also not rated as excessive (275ppm).

4. Conclusions

This study concentrated on assessment of top soil parameters as most coffee feeder roots are found near the surface. Soil properties were found to be spatially variable especially in the top depth, with the exception of micronutrients. Across the parameters, the spatial variability was predominantly moderate. Based on the findings, farm decisions should be based on the soil management zones to ensure precise input application. Phosphorus was the most deficient nutrient which can be attributed to soil genesis from a P-deficient parent material. It could also be due to the predominantly acidic soil reaction that could have resulted to fixing of P sources. There is need to apply manure to the soils due to its vital role in maintaining high organic matter and indirectly maintaining nitrogen and phosphorus sources in the soil. Micronutrients sufficiency in the studied farm can be attributed to the predominantly acidic soil reaction as micronutrient availability increases with increasing soil acidity. There is need to prevent soil erosion in the farm so as to maintain high soil and water quality. NPK fertilizer preferably 40:30:40 is recommended, to be applied in three splits. Input management based on spatial variability of soil properties is highly recommended so as to get maximum output using optimum inputs. Training on spatial variability and precision agriculture in colleges, universities and research institutions is highly recommended so that it can be included in extension services to farmers. Envisaging high value crops where they best fit is also recommended.

Declarations

Author contribution statement

Samuel Mwendwa, Joseph P. Mbuvi: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Geoffrey Kironchi, Charles K.K. Gachene: Conceived and designed the experiments; Wrote the paper.

Funding statement

The purchase of laboratory reagents was supported by Prof. J.P Mbuvi.

Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

The main author acknowledges Prof. J.P Mbuvi of University of Nairobi, for his generous financial support that made this study possible.

References

- Adhikari, T., Sarkar, D., Mashayekhi, H., Xing, B., 2016. Growth and enzymatic activity of maize (*Zea mays* L.) plant: solution culture test for copper dioxide nano particles. *J. Plant Nutr.* 39 (1), 99–115.
- Alwell, C., Ringeval, B., Ballabio, C., Robinson, D.A., Panagos, P., Borrelli, P., 2020. Global phosphorus shortage will be aggravated by soil erosion. *Nat. Commun.* 11, 4546.
- Ali, A., Martelli, R., Lupia, F., Barbanti, L., 2019. Assessing multiple years' spatial variability of crop yields using satellite vegetation indices. *Rem. Sens.* 11, 2384.
- Ali, A., Rondelli, V., Martelli, R., Falsone, G., Lupia, F., Barbanti, L., 2022. Management zones delineation through clustering techniques based on soils traits, NDVI data, and multiple year crop yields. *Agriculture* 231, 12.
- Aubert, B.A., Schroeder, A., Grimaudo, J., 2012. IT as enabler of sustainable farming: an empirical analysis of farmers' adoption decision of precision agriculture technology. *Decis. Support Syst.* 54 (1), 510–520.
- Baillie, I.C., Anderson, J.M., Ingram, J.S.I., 1990. Tropical soil biology and fertility: a handbook of methods. *J. Ecol.* 78 (2), 547.
- Bakhshandeh, S., Norouzi, M., Heidari, S., Bakhshandeh, S., 2014. The role of parent material on soil properties in sloping areas under tea plantation in Lahijan, Iran. *Carpathian J. Earth Environ. Sci.* 9 (3), 159–170.
- Bao-wei, S., Geng-xing, Z., Chao, D., 2018. Spatio-temporal variability of soil nutrients and the responses of growth during growth stages of winter wheat in the north of China. *PLoS One* 13, e398701.
- Basso, B., Ritchie, J.T., Cammarano, D., Sartori, L., 2011. A strategic and tactical management approach to select optimal N fertilizer rates for wheat in a spatially variable field. *Eur. J. Agron.* 35 (4), 215–222.
- Bauer, S., 2014. United Nations environment programme. In: *Essential Concepts of Global Environmental Governance*.
- Behera, Sanjib K., Suresh, K., Rao, B.N., Mathur, R.K., Shukla, A.K., Manoraja, K., Ramachandrudu, K., Harinarayana, P., 2016. Spatial variability of some soil properties in west coastal area of India having oil palm (*Elaeis guineensis* Jacq.) plantations. *Solid Earth Discussions*, January 1–33.
- Behera, Sanjib Kumar., Shukla, A.K., 2015. Spatial distribution of surface soil acidity, electrical conductivity, soil organic carbon content and exchangeable potassium, calcium and magnesium in some cropped acid soils of India. *Land Degrad. Dev.* 26 (1), 71–79.
- Black, C.A., 1965. *Methods of Soil Analysis. Part I and II.* Amer. Soc. Agron., Madison, Wisconsin.
- Blanco, E., Fortunato, S., Viggiano, L., de Pinto, M.C., 2020. Cyclic AMP: a polyhedral signalling molecule in plants. *Int. J. Mol. Sci.* 21 (14), 4862.
- Brevik, E.C., Miller, B.A., 2015. The use of soil surveys to aid in geologic mapping with an emphasis on the Eastern and MidWestern United States. *Soil Horiz.* 56 (4).
- Browaldh, M., 1995. The influence of trees on nitrogen dynamics in an agrisilvicultural system in Sweden. *Agrofor. Syst.* 30 (3), 301–313.
- Castaldi, F., Pelosi, F., Pascucci, S., Casa, R., 2017. Assessing the potential of images from unmanned aerial vehicles (UAV) to support herbicide patch spraying in maize. *Precis. Agric.* 18 (1), 76–94.
- Cheng, W., Padre, A.T., Sato, C., Shiono, H., Hattori, S., Kajihara, A., Aoyama, M., Tawaraya, K., Kumagai, K., 2016. Changes in the soil C and N contents, C decomposition and N mineralization potentials in a rice paddy after long-term application of inorganic fertilizers and organic matter. *Soil Sci. Plant Nutr.* 62 (2), 212–219.
- de Bang, T.C., Husted, S., Laursen, K.H., Persson, D.P., Schjoerring, J.K., 2021. The molecular-physiological functions of mineral macronutrients and their consequences for deficiency symptoms in plants. *New Phytol.* 229 (5), 2446–2469.
- Ducousso-Détrez, A., Fontaine, J., Lounès-Hadj Sahraoui, A., Hijri, M., 2022. Diversity of phosphate chemical forms in soils and their contributions on soil microbial community structure changes. *Microorganisms* 10, 609.
- Eastwood, C., Klerkx, L., Nettle, R., 2017. Dynamics and distribution of public and private research and extension roles for technological innovation and diffusion: case studies of the implementation and adaptation of precision farming technologies. *J. Rural Stud.* 49, 1–12.
- Emadi, M., Shahriari, A.R., Sadegh-Zadeh, F., Jalili I-Bardan, B., Dindarlou, A., 2016. Geostatistics-based spatial distribution of soil moisture and temperature regime classes in Mazandaran province, northern Iran. *Arch. Agron Soil Sci.* 62 (4), 502–522.
- Fageria, N.K., Santos, A.B., Barbosa Filho, M.P., Guimarães, C.M., 2008. Iron toxicity in lowland rice. *J. Plant Nutr.* 31 (9), 1676–1697.
- Farzadfar, S., Knight, J.D., Congreves, K.A., 2021. Soil organic nitrogen: an overlooked but potentially significant contribution to crop nutrition. *Plant Soil* 462, 7–23.
- Ferreira, C.S., Seifollahi-Aghmiuni, S., Destouni, G., Ghajarnia, N., Kalantari, Z., 2022. Soil degradation in the European Mediterranean region: processes, status and consequences. *Sci. Total Environ.* 805, 150106.
- Franzuebbers, A.J., Hons, F.M., 1996. Soil-profile distribution of primary and secondary plant-available nutrients under conventional and no tillage. *Soil Tillage Res.* 39 (3–4), 229–239.
- Fridgen, J.J., Kitchen, N.R., Sudduth, K.A., Drummond, S.T., Wiebold, W.J., Fraisse, C.W., 2004. Management zone analyst (MZA): software for subfield management zone delineation. *Agron. J.* 96 (1), 100–108.
- Goovaerts, P., 1998. Geostatistical tools for characterizing the spatial variability of microbiological and physico-chemical soil properties. *Biol. Fertil. Soils* 27 (4), 315–334.
- Hălbac-Cotoară-Zamfir, R., Keesstra, S., Kalantari, Z., 2019. The impact of political, socio-economic and cultural factors on implementing environment friendly techniques for sustainable land management and climate change mitigation in Romania. *Sci. Total Environ.* 654, 418–429.
- Hao, Z., Wang, Y., Ding, N., Saha, M.C., Scheible, W.R., Craven, K., et al., 2022. Spectroscopic analysis reveals that soil phosphorus availability and plant allocation strategies impact feedstock quality of nutrient-limited switchgrass. *Commun. Bio.* 5 (1), 1–9.
- Jatzold, R., Kutsch, H., 1982. Agro-ecological zones of the tropics, with a sample from Kenya. *J. Agric. Trop. Subtrop.* 83, 15–34.
- Kandagor, D.C., 2015. Evaluation of Spatial Variability of Selected Soil Chemical Properties, Their Influence on Coffee Yields and Management Practices at Kabete Field Station farm.Pdf.
- Kathumo, V.M., 2007. Establishment of Soil Management Zones Based on Spatial Variability of Soil Properties for Precision Agriculture Using GIS in Katumani, Machakos District of Kenya. MSc. Thesis. University of Nairobi.
- Keesstra, S.D., Bouma, J., Wallinga, J., Tittone, P., Smith, P., Cerda, A., Montanarella, L., Quinton, J.N., Pachepsky, Y., Van Der Putten, W.H., Bardgett, R.D., Moolenaar, S., Mol, G., Jansen, B., Fresco, L.O., 2016. The significance of soils and soil science towards realization of the United Nations sustainable development goals. *Soils* 2 (2), 111–128.
- Khadka, D., Lamichhane, S., Tiwari, D., 2017. Assessment of Soil Fertility Status of National rice Research.
- Lecourieux, D., Ranjeva, R., Pugin, A., 2006. Calcium in plant defence-signalling pathways: tansley review. *New Phytol.* 171 (2), 249–269.
- Lelago, A., Buraka, T., 2019. Determination of physico-chemical properties and agricultural potentials of soils in Tembaro district, Kembattembaro zone, southern Ethiopia. *Eurasian J. Soil Sci.* 8 (2), 118–130.
- Li, X., Liang, Z., Li, Y., Zhu, Y., Tian, X., Shi, J., Wei, G., 2021. Short-term effects of combined organic amendments on soil organic carbon sequestration in a rain-fed winter wheat system. *Agron. J.* 113, 2150–2164.
- Lindblom, J., Lundström, C., Ljung, M., Jonsson, A., 2017. Promoting sustainable intensification in precision agriculture: review of decision support systems development and strategies. *Precis. Agric.* 18 (3), 309–331.
- Liu, C.L., Wu, Y.Z., Liu, Q.J., 2015. Effects of land use on spatial patterns of soil properties in a rocky mountain area of Northern China. *Arabian J. Geosci.* 8 (2), 1181–1194.
- Liu, J., Yang, H., Zhao, M., Zhang, X.H., 2014. Spatial distribution patterns of benthic microbial communities along the Pearl Estuary, China. *Syst. Appl. Microbiol.* 37 (8), 578–589.
- Llewellyn, R., Ouzman, J., 2014. *Adoption of Precision Agriculture-Related Practices: Status, Opportunities and the Role of Farm Advisers.* CSIRO Report Published by GRDC. <https://grdc.com.au/Resources/Publications/2014/12/Adoption-of-precision-agriculture-related-practices>.
- Lundström, C., Lindblom, J., 2016. Considering farmers' situated expertise in using AgriDSS to foster sustainable farming practices in precision agriculture. *Proceedings of the 13th International Conference on Precision Agriculture* 1–15.
- Madigan, A.P., Zimmermann, J., Krol, D.J., Williams, M., Jones, M.B., 2022. Full Inversion Tillage (FIT) during pasture renewal as a potential management strategy for enhanced carbon sequestration and storage in Irish grassland soils. *Sci. Total Environ.* 805, 150342.
- Maleki, A., Fazel, S., Naseri, R., Rezaei, K., Heydari, M., 2014. The effect of potassium and zinc sulfate application on grain yield of maize under drought stress conditions. *Adv. Environ. Biol.* 8 (4), 890–893.
- Marschner, H., 1995. *Mineral Nutrition of High Plant.* Academic Press, pp. 330–355.
- Mathu, E., Mwea, S.K., 2014. A study on the engineering behaviour of Nairobi subsoil. *ARNP J. Eng. Appl. Sci.* 6, 7.
- McBratney, A.B., Mendonça Santos, M.L., Minasny, B., 2003. On digital soil mapping. *Geoderma* 117, Issues 1–2.
- McEntee, P.J., Bennett, S.J., Belford, R.K., 2020. Mapping the spatial and temporal stability of production in mixed farming systems: an index that integrates crop and pasture productivity to assist in the management of variability. *Precis. Agric.* 21, 77–106.
- Moosavi, A.A., Sepaskhah, A.R., 2012. Spatial variability of physico-chemical properties and hydraulic characteristics of a gravelly calcareous soil. *Arch. Agron Soil Sci.* 58 (6), 631–656.
- Moradi, F., Moosavi, A.A., Moghaddam, B.K., 2016. Spatial variability of water retention parameters and saturated hydraulic conductivity in a calcareous Inceptisols (Khuzestan province of Iran) under sugarcane cropping. *Arch. Agron Soil Sci.* 62 (Issue 12).
- Morari, F., Zanello, V., Sartori, L., Visioli, G., Berzaghi, P., Mosca, G., 2018. Optimising durum wheat cultivation in North Italy: understanding the effects of site-specific fertilization on yield and protein content. *Precis. Agric.* 19 (2), 257–277.

- Mugendi, D., Mucheru-Muna, M., Mugwe, J., Kung'u, J., Bationo, A., 2007. Improving food production using 'best bet' soil fertility technologies in the Central highlands of Kenya. *Advances in Integrated Soil Fertility Management in Sub-Saharan Africa: Challenges and Opportunities* 345–351, 1996.
- Muschietti-Piana, M. del P., Cipriotti, P.A., Urricariet, S., Peralta, N.R., Niborski, M., 2018. Using site-specific nitrogen management in rainfed corn to reduce the risk of nitrate leaching. *Agric. Water Manag.* 199, 61–70.
- Muyanga, M., Jayne, T.S., 2014. Effects of rising rural population density on smallholder agriculture in Kenya. *Food Pol.* 48, 98–113.
- Mwendwa, S., Mbuvi, J., Kironchi, G., Gachene, C., 2020. A geopedological approach to soil classification to characterize soils of upper Kabete campus field, university of Nairobi, Kenya. *Trop. Subtropical Agroecosys.* 23 (2). Retrieved from <http://www.revista.criba.uady.mx/ojs/index.php/TSA/article/view/2836/1432>.
- Mwendwa, S.M., Mbuvi, J.P., Kironchi, G., 2019. Land evaluation for crop production in upper Kabete campus field. University of Nairobi, Kenya. *Chemical and Biological Technologies in Agriculture* 6 (1).
- Nadeem, M., Wu, J., Ghaffari, H., Kadir, A.J., Saleem, S., Mollier, A., et al., 2022. Understanding the adaptive mechanisms of plants to enhance phosphorus use efficiency on podzolic soils in boreal agroecosystem. *Front. Plant Sci.* 337.
- Nelson, E.W., Sommers, L.E., 1996. Total carbon, organic carbon, and organic matter. In: Sparks, D.L. (Ed.), *Methods of Soil Analysis: Chemical Methods. Part 3. Soil Science Society of America, Madison WI*.
- Ng, J.F., Ahmed, O.H., Jalloh, M.B., Omar, L., Kwan, Y.M., Musah, A.A., Poong, K.H., 2022. Soil nutrient retention and pH buffering capacity are enhanced by calciprill and sodium silicate. *Agronomy* 12 (1), 219.
- Nyéki, A., Kerepesi, C., Daróczy, B., Benczúr, A., Milics, G., Nagy, J., Harsányi, E., Kovács, A.J., Neményi, M., 2021. Application of spatio-temporal data in site-specific maize yield prediction with machine learning methods. *Precis. Agric.* (22), 1397–1415.
- Nyéki, A., Daróczy, B., Kerepesi, C., Neményi, M., Kovács, A.J., 2022. Spatial variability of soil properties and its effect on maize yields within field-A case study in Hungary. *Agronomy* 12, 395.
- Nzeyimana, I., Hartemink, A.E., Ritsema, C., Mbonigaba, J.J.M., Geissen, V., 2020. Mulching effects on soil nutrient levels and yield in coffee farming systems in Rwanda. *Soil Use Manag.* 36 (1), 58–70.
- Onyancha, C., Mathu, E., Mwea, S., Ngecu, W., 2011. A study on the engineering behaviour of Nairobi subsoil. *J. Eng. Appl. Sci.* 6 (7), 85–96.
- Panday, D., Maharjan, B., Chalise, D., Kumar Shrestha, R., Twanabasu, B., 2018. Digital soil mapping in the Bara district of Nepal using kriging tool in ArcGIS. *PLoS One* 13 (10), 1–20.
- Panday, D., Ojha, R.B., Chalise, D., Das, S., Twanabasu, B., 2019. Spatial variability of soil properties under different land use in the Dang district of Nepal. *Cogent Food Agri.* 5 (1), 1600460.
- Pendleton, R.L., Jenny, H., 1945. Factors of soil formation: a system of quantitative pedology. In: *geographical review*, 35. Dover Publications, 2.
- Porder, S., Ramachandran, S., 2013. The phosphorus concentration of common rocks—a potential driver of ecosystem P status. *Plant Soil* 367 (1–2), 41–55.
- Rai, S., Chopra, A.K., Pathak, C., Sharma, D.K., Sharma, R., Gupta, P.M., 2011. Comparative study of some physicochemical parameters of soil irrigated with sewage water and canal water of Dehradun city, India. *Arch. Appl. Sci. Res.* 3 (2), 318–325.
- Ringeval, B., Augusto, L., Monod, H., Van Apeldoorn, D., Bouwman, L., Yang, X., et al., 2017. Phosphorus in agricultural soils: drivers of its distribution at the global scale. *Global Change Biol.* 23 (8), 3418–3432.
- Robertson, M.J., Llewellyn, R.S., Mandel, R., Lawes, R., Bramley, R.G.V., Swift, L., Metz, N., O'Callaghan, C., 2012. Adoption of variable rate fertiliser application in the Australian grains industry: status, issues and prospects. *Precis. Agric.* 13 (2), 181–199.
- Schad, P., 2017. World reference base for soil resources. In: *Reference Module in Earth Systems and Environmental Sciences*.
- Scudiero, E., Teatini, P., Manoli, G., Braga, F., Skaggs, T., Morari, F., 2018. Workflow to establish time-specific zones in precision agriculture by spatiotemporal integration of plant and soil sensing data. *Agronomy* 8, 253.
- Shahabi, M., Jafarzadeh, A.A., Neyshabouri, M.R., Ghorbani, M.A., Kamran, K.V., 2016. Spatial adaptability of soil salinity using multiple linear regression, ordinary kriging and artificial neural network methods. *Arch. Agron Soil Sci.*
- Shukla, A.K., Behera, S.K., Lenka, N.K., Tiwari, P.K., Prakash, C., Malik, R.S., Sinha, N.K., Singh, V.K., Patra, A.K., Chaudhary, S.K., 2016. Spatial variability of soil micronutrients in the intensively cultivated Trans-Gangetic Plains of India. *Soil Tillage Res.* 163, 282–289.
- Smith, B.C.M., Dhuyvetter, K.C., Kastens, T.L., Dietrich, L., Smith, L.M., 2013. Economics of precision agricultural technologies across the great plains. *J. Am. Soc. Farm Manag. Rural A* 76 (1), 185–206.
- Sumithra, S., C, A., D, R., Rt, Y., 2013. A case study on physico-chemical characteristics of soil around industrial and agricultural area of Yerraguntla, Adapa district, A. P., India. *Int. J. Geology, Earth Environ. Sci.* 3 (2), 28–34.
- Swoboda, P., Döring, T.F., Hamer, M., 2022. Remineralizing soils? The agricultural usage of silicate rock powders: a review. *Sci. Total Environ.* 807, 150976.
- Tanoi, K., Kobayashi, N.I., 2015. Leaf senescence by magnesium deficiency. *Plants* 4 (4), 756–772.
- Ullah, M.A., Anwar, M., Rana, A.S., 2010. Effect of nitrogen fertilization and harvesting intervals on the yield and forage quality of elephant grass (*Pennisetum purpureum* L.) under mesic climate of Pothowar plateau. *Pak. J. Agri. Science* 47, 231–234.
- Uthman, Q.O., Kadyampakeni, D.M., Nkedi-Kizza, P., Kwakye, S., Barlas, N.T., 2022. Boron, manganese, and zinc sorption and leaf uptake on citrus cultivated on a sandy soil. *Plants* 11 (5), 638.
- Veedhi, A., 2008. *Coffee Cultivation Guide for South-West Monsoon Area Growers in India (Coffee Kaipidi)*. Central Coffee Research Institute, Karnataka, India, p. 231.
- Willy, D.K., Muyanga, M., Mbuvi, J., Jayne, T., 2019. The effect of land use change on soil fertility parameters in densely populated areas of Kenya. *Geoderma* 343 (September 2018), 254–262.
- Wolfert, S., Ge, L., Verdouw, C., Bogaardt, M.J., 2017. Big data in smart farming – a review. *Agric. Syst.* 153, 69–80.
- World, 2007. *Development Report 2008 (Overview)*. In *World Development Report 2008 (Overview)* (Issue c).
- Wu, Z., Liu, Y., Li, G., Han, Y., Li, X., Chen, Y., 2022. Influences of environmental variables and their interactions on Chinese farmland soil organic carbon density and its dynamics. *Land* 11, 208.
- Yadegari, M., 2014. Irrigation periods and Fe, Zn foliar application on agronomic characters of medicinal plants. *Adv. Environ. Biol.* 8 (4), 1054–1062.
- Yan, P., Peng, H., Yan, L., Zhang, S., Chen, A., Lin, K., 2019. Spatial variability in soil pH and land use as the main influential factor in the red beds of the Nanxiong Basin, China. *PeerJ* 2019 (1), 1–22.
- Ye, Y., Jiang, Y., Kuang, L., Han, Y., Xu, Z., Guo, X., 2021. Predicting spatial distribution of soil organic carbon and total nitrogen in a typical human impacted area. *Geocart Int.* 1–19.
- Zhang, Q., Tang, D., Yang, X., Geng, S., He, Y., Chen, Y., et al., 2021. Plant availability of magnesium in typical tea plantation soils. *Front. Plant Sci.* 1579.
- Zhao, Z., Gao, S., Lu, C., Li, X., Li, F., Wang, T., 2021. Effects of different tillage and fertilization management practices on soil organic carbon and aggregates under the rice-wheat rotation system. *Soil Tillage Res.* 212, 105071.